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Application of optical methods in tests of new materials with gradient structure

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Abstract. The main idea of the article is to demonstrate the possibility of applying the laser dynamic speckle interferometry technique to control the processes of fatigue failure of specimens with a gradient structure. A distinctive feature of the described technique is the possibility of practical application on high-frequency machines as an experimental non-contact method for recording surface changes in the studying objects with a complex structure. Besides, the proposed technique can be used as an indicator characterizing irreversible processes during fatigue failure and for analyzing the fatigue crack growth kinetics.

1. Introduction

At present finding the fracture precursors of structural elements as well as monitoring existing fracture centers under conditions of multi-cycle fatigue loading is an urgent not yet completely solved task. Among the existing methods for observing the fracture process, such as the use of contact measuring instruments (strain gauges, foils, piezoelectric elements) and non-contact based on measurements of magnetic and thermal properties optical methods deserve special attention. One of the most common and widely used optical control methods is the Digital Image Correlation method (DIC) [1]. At the same time tests not of standard samples, but of structural elements, including, among other things, materials of a new generation (for example, composites or products obtained by additive technologies) are finding increasing application. However, the use of DIC in the analysis of the fracture kinetics of materials with complex geometry under high-frequency fatigue loading is difficult due to the shallow depth of field, which is due to the wide field of view, relatively low sensitivity and implementation features of the algorithm for constructing strain distribution diagrams, which does not allow controlling the object when exposed to small loads. The methods of electronic speckle interferometry and holographic interferometry which are successfully used in non-destructive testing of materials and products to detect defects that cannot be detected by visual examination are devoid of these disadvantages [2].



Holographic interferometry allows you to solve many problems, such as defect detection, strain analysis, object shape control, etc. A variety of methods of holographic interferometry is based on the principle of comparing two wavefronts, one of them or both being recorded and restored using the holographic method [3]. Speckle interferometry, as well as holographic interferometry, allows you to measure displacements (static and dynamic) and to research the relief of an optically rough surface with sensitivity on the order of the light wavelength. And with the use of computer technology the removal and processing of images no longer takes a lot of time which can significantly expand the scope of this method. Besides, coherence methods use a small diaphragm size to increase the depth of field which is especially important when examining objects with a complex structure.

2. Materials and methods

In the present work, the results of researching the fatigue crack growth kinetics, the evolution of the size and shape of the plastic deformation zone during its nucleation and propagation are presented. Results are obtained using a technique based on recording changes in speckle images of the testing objects surface - laser dynamic speckle interferometry which was successfully used earlier to research processes of plastic deformation and fracture of metals under conditions of quasistatic loading [4, 5].

As objects of research metal products were selected that have a significant gradient in the structure or distribution of properties over the cross-section — a gas turbine engine guide blade, a titanium alloy Ti-6Al-4V with a cellular structure, obtained on a 3D printer (EOS 280), and a layered metal composite material consisting of alternating layers of low-carbon steels 09G2S and EP678. The speckle images of the surfaces of the researched objects and the distribution of the correlation coefficients of their fragments recorded directly during cyclic loading are shown in Fig. 1-3.

Fatigue loading was performed on an MIKROTRON RUMUL high-frequency resonance testing machine using three-point bending (for layered composite), cantilever bending (turbine blade) and uniaxial compression-compression (Ti-6Al-4V alloy) schemes. The loading frequency ranged from 70 to 110 Hz.

The research of the features of fracture and localization of the fatigue crack nucleation region, the evolution of the size and shape of the plastic deformation zone during its nucleation and propagation, was carried out using laser dynamic speckle interferometry techniques. It is based on finding the correlation of two frames of speckle images recorded at different stages of cyclic loading. Speckle images of the object were recorded using an optical device consisting of a laser module with a wavelength of 650 nm, a power of 40 mW, and a USB video camera VIDEOSKAN-415M [6].

One of the advantages of the technique is the ability to work in real-time, so it is possible to obtain pictures of averaging speckles over the time range of the exposure time of the camera. For each type of loading the optimal conditions for fixing images and the parameters for constructing correlation patterns (the step between the compared images, the minimum and maximum values of the correlation coefficient, the size of the cells into which the image is divided during calculations) were selected. All calculations are based on a modern hardware and software system that allows you to compare information with data obtained directly from the testing machine [7].

3. Results and discussion

According to the results of fatigue tests of gas turbine engines blades made of VT3-1 titanium alloy, it is shown that the dynamic speckle interferometry method allows us to unambiguously record the initial stage of formation of the fatigue fracture center on the blades near the fillet (Figure 1, b), which was also confirmed by a change in the resonance loading frequencies. Subsequent loading led to the growth of a fatigue crack and upon reaching 5×10^6 cycles, the length of the fatigue crack was 2 mm. According to the results of speckle image processing, the growth trajectory of the fatigue crack was established as well as the shape and size of the localized zone of plastic deformation at the crack tip.

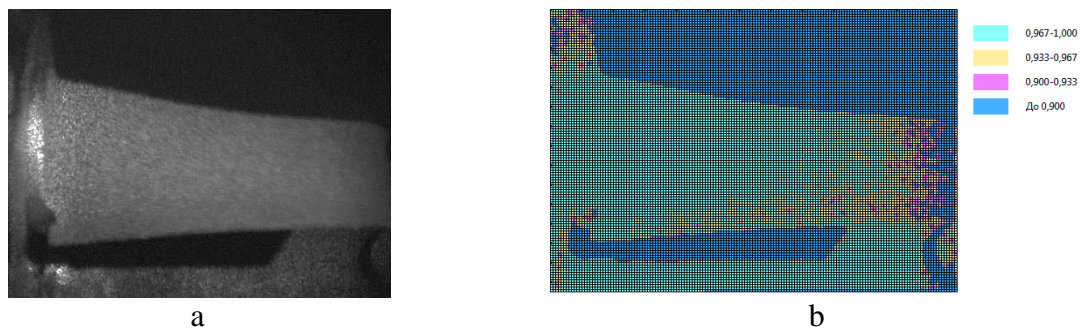


Figure 1. Typical speckle image (a) and distribution of correlation coefficients for speckle image fragments (b) of a gas turbine engine blade.

Samples of a titanium alloy with a cellular structure, that is, with a periodic arrangement of pores of a given geometry, obtained by layer-by-layer fusion of the powder, have a difference in the relative surface height of up to 2 mm. Besides, the complex geometric structure is supplemented by production features that can cause anisotropy of the material properties, and therefore, the fracture can occur randomly in different areas, which greatly complicates the analysis of the fracture kinetics. Based on the results of the tests it was shown the possibility of processing images of a similar class of objects under cyclic loading and the program settings for processing speckle images have been selected (Fig. 2).

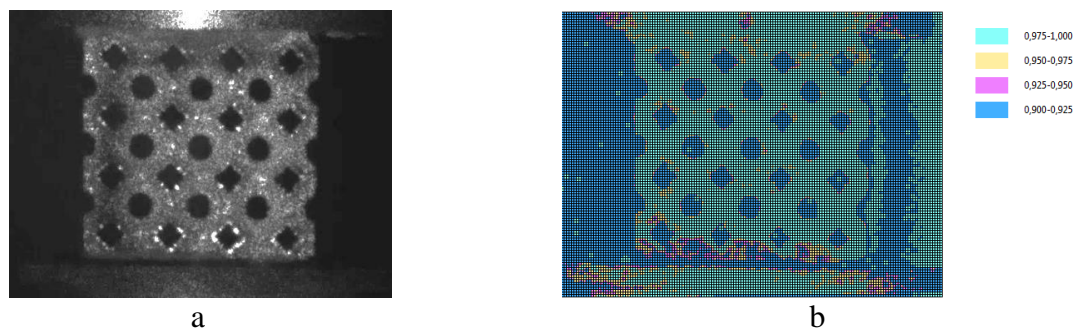


Figure 2. Typical speckle image (a) and distribution of correlation coefficients of speckle image fragments (b) of a titanium alloy sample Ti-6Al-4V.

Using the example of a layered metal composite material of the steel-steel system, the features of the intersections of a layer connecting boundary by a fatigue crack were revealed and the dominant mechanisms of fatigue crack retardation were analyzed [8].

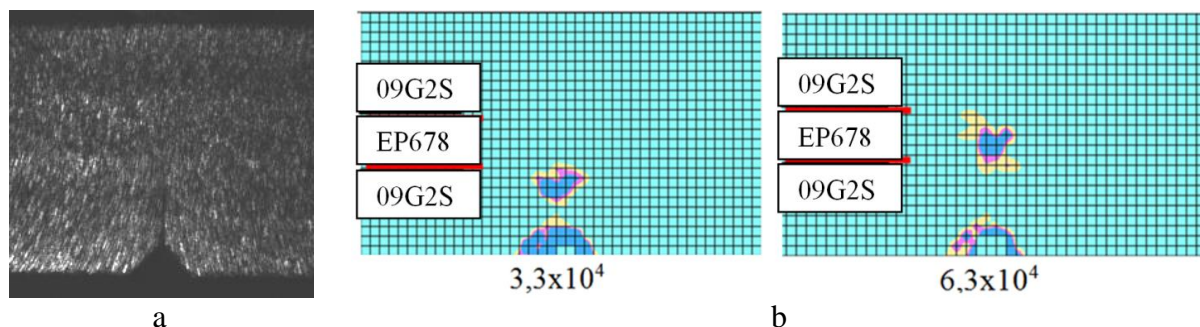


Figure 3. Typical speckle image (a) and distribution of correlation coefficients of speckle image fragments (b) of a sample from a layered composite of the steel-steel system.

4. Conclusion

Thus, on the example of fatigue tests of a different class of objects with a gradient structure the possibilities of using the laser dynamic speckle interferometry technique to control fracture processes are shown. It should be emphasized that the developed speckle interferometric technique allows us to determine in situ such an important parameter of fracture mechanics as the size of the localized plastic deformation zone at the crack tip. This parameter is unambiguously related to the stress intensity coefficient characterizing the ability of the material to brittle fracture in the vicinity of the fracture focus. Moreover, since the stress intensity factor is invariant to the geometry of the controlled object, its value determined on standard samples can also be used to assess the level of accumulated damage to structural elements from the same materials as standard samples. A distinctive feature is the possibility of practical application on high-frequency machines as an experimental non-contact method for recording changes in the objects under research with a complex structure.

The proposed technique can be used as an indicator characterizing irreversible processes during fatigue failure and for analyzing the fatigue crack growth kinetics. The obtained experimental results indicate the possibility of reliable registration of the fatigue failure formation stages and crack propagation during cyclic loading. The registration of various stages of material fatigue degradation is fundamentally important for determining the limits of applicability of the approaches of damage mechanics and fracture mechanics which are used in assessing the durability of objects.

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